EVALUATION OF THE SWAT MODEL ON A COASTAL PLAIN AGRICULTURAL WATERSHED

D. D. Bosch, J. M. Sheridan, H. L. Batten, J. G. Arnold

ABSTRACT. *The Better Assessment Science Integrating point and Nonpoint Sources (BASINS) system was developed by the U.S. Environmental Protection Agency to facilitate developing total maximum daily loads (TMDLs). The Soil Water Assessment Tool (SWAT) is one of the watershed−scale simulation models within BASINS. Because of the critical nature of the TMDL process, it is imperative that BASINS and SWAT be adequately validated for regions on which they are being applied. BASINS and SWAT were tested using six years of hydrologic data from a 22 km² subwatershed of the Little River in Georgia. Comparisons were made between water balance results obtained using high and low spatial resolution data as well as those obtained using default initial parameters versus those modified for existing groundwater conditions. In general, all scenarios simulated general trends in the observed flow data. However, for the years with lower precipitation, the total water yields simulated with the low spatial resolution data and the default initial conditions were overpredicted by up to 27% of the annual precipitation input. Total water yields simulated using the high spatial resolution input data were within 20% of the observed yields for each year of the assessment. Nash−Sutcliffe model efficiencies (E) for monthly total water yields were 0.80 using the high spatial resolution data with the modified initial conditions and 0.64 using the low spatial resolution data with the default initial conditions. While the model simulated general streamflow trends, discrepancies were observed between observed and simulated hydrograph peaks, time to peak, and hydrograph durations. A one−day time lag between the simulated and observed time to peak was the primary cause of large errors in daily flow simulations. Model modification and more extensive calibration may be necessary to increase the accuracy of the daily flow estimates for TMDL development.*

Keywords. *Hydrologic modeling, Streamflow, Watersheds.*

Water is our most valuable resource. Realizing its value, states and nations often argue over water rights and protection. An increasing awareness of the value of water has resulted in considerable improvement in water conservation and preservation. Over the past 20 years, substantial reductions have been achieved in the discharge of pollutants into the lakes, rivers, wetlands, estuaries, coastal waters, and groundwater. Despite significant progress in reducing pollution, over 40% of the assessed waters in the U.S. still do not meet set standards (www.epa.gov/owow/tmdl/). These waters amount to over 20,000 individual river segments, lakes, and estuaries, including nearly 500,000 km of rivers and shorelines and approximately 2 million ha of lakes.

Public awareness of these problems led to the passage of the Clean Water Act in 1972. The Clean Water Act stimulated huge reductions in point−source pollution. It also paved the way for the current Total Maximum Daily Load (TMDL) program, which is addressing nonpoint−source pollutant loading to water bodies within the U.S. (U.S. EPA, 1998; National Research Council, 2001; Bosch, 2003a, 2003b). The program has become very political, with strong concerns expressed over jurisdiction and responsibility. However, significant progress has been made by increasing public awareness of water pollution and its importance to public health and well being.

The TMDL process provides an assessment and planning framework for identifying load reductions or other actions needed to attain set standards (i.e., goals to protect aquatic life, drinking water, and other water uses). A key component is the identification of the pollutant, largely accomplished through monitoring, and the identification of a remedy. The identification of a remedy is largely accomplished by examining the feasibility of implementing various best management practices (BMPs) and assessing the impact they would have on pollutant loading. This assessment is often accomplished through computer simulations of the physical processes. In most cases, the TMDL implementation plan is developed through a combination of observations and model simulations. Because of the critical nature of the process, it is imperative that these models be validated for the constituents they are being used to simulate and evaluated to determine how well they perform under a variety of conditions.

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Under the Clean Water Act, the U.S. EPA was given the authority to implement pollution control programs and set water quality standards for all surface water contaminants. The EPA and its counterparts in states and pollution control agencies are increasingly emphasizing watershed and water quality−based assessment and integrated analysis of point and nonpoint sources. To facilitate this, the EPA developed the Better Assessment Science Integrating point and Nonpoint Sources (BASINS) system (U.S. EPA, 2001). BASINS integrates a geographic information system (GIS), national watershed and meteorological data, and state−of−the−art environmental assessment and modeling tools into one software package. To simplify the development of TMDLs across the nation, a data set has been assembled, which can be easily retrieved for use with BASINS. These data are readily available through the U.S. Geological Survey (USGS) and the EPA, and are distributed by the EPA on its website for BASINS. Because they are readily available, these data sets are often used for developing TMDLs. However, it is not known how well the characteristics represented by the data sets within BASINS represent actual land−use and geologic conditions. Moreover, the accuracy obtained when the BASINS default data sets are used for simulation purposes has not been quantified.

BASINS contains three models for estimating watershed loading. These models include a simplified GIS−based nonpoint−source loading model (PLOAD) and two physically based watershed loading and transport models, Hydrologic Simulation Program−Fortran (HSPF) and Soil and Water Assessment Tool (SWAT). SWAT is a river basin model developed to quantify the impact of land management practices in large watersheds (Arnold et al., 1998). SWAT was developed to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large watersheds with varying soils, land−use, and management conditions over long periods of time. The major components of the model include hydrology, weather, erosion and sediment transport, soil temperature, crop growth, agrichemical transport, and agricultural management.

Watershed models are valuable tools for examining the impact of land−use on hydrology and water quality. While extensive research has been done to describe the impact of management practices on field and farm runoff, less is known about how these changes are reflected at the watershed scale. The success of the TMDL program will be based on the water quality improvements that result from the program. The SWAT model has been applied to watersheds throughout the world. The model has received extensive testing in Texas, where it was used to simulate hydrologic and water quality responses in a watershed with considerable livestock production and to examine BMPs within the watershed (Saleh et al., 2000; Santhi et al., 2001). Simulated hydrologic and water quality data agreed well with observed data in these studies. The model has been applied to watersheds of varying size, from the 598,538 km^2 Rio Grande/Rio Bravo river basin (Srinivasan et al., 1997) to a 5.5 km^2 watershed in north−central Kentucky (Spruill et al., 2000). Additional testing of the model has been conducted on a 9,708 km^2 watershed in Wisconsin (Kirsch et al., 2002), a 21.3 km^2 watershed in Mississippi (Bingner, 1996), watersheds from 3.3 to 113.4 km^2 in west−central Indiana (Smithers and Engel, 1996), and a 39.5 km^2 watershed in northeastern Pennsylvania (Peterson and Hamlett, 1998). In most cases, the prediction accuracy was satisfactory to obtain working knowledge of the hydrologic system and the processes occurring in the watersheds. The accuracy of the model generally improved when annual and monthly data were examined as opposed to daily values. The results of these studies are promising. However, additional research needs to be conducted to validate the model for regions of the U.S. with contrasting climates, hydrology, geology, and land−use.

The primary transport mechanism of many environmental contaminants is through water flow. Because of this, accurate simulation of the hydrologic component of the system is a prerequisite for accurate contaminant transport modeling. In this analysis, we tested the hydrologic component of the SWAT model. The analysis characterizes the accuracy of simulations obtained using the SWAT model with readily available BASINS GIS coverages, the improvements in hydrologic simulation accuracy that can be expected by using higher resolution land−use, soils, and topographic coverages, and the improvements that can be expected through limited modification of parameters describing initial groundwater conditions. These assessments are necessary to evaluate the utility of BASINS for TMDL development in this region. Because TMDLs will be developed for many ungauged watersheds, it is unreasonable to expect the models to be extensively calibrated during the process. Specific objectives of this research were to: (1) evaluate the effectiveness of SWAT for simulating the hydrology of a 22.1 km^2 Coastal Plain watershed in the southeastern U.S., and (2) evaluate the accuracy of simulation results obtained using data sets readily available through the national data base incorporated within BASINS. Hydrologic, geographic, and land−use data collected by the Southeast Watershed Research Laboratory for the Little River watershed in south−central Georgia (Sheridan et al., 1995) were used to evaluate the accuracy of the model and the feasibility of model application for the southeastern Coastal Plain of the U.S.

Methods

Little River Watershed

The hydrology and water quality of the Little River watershed (LRW) near Tifton, Georgia, in the South Atlantic Coastal Plain have been studied since the late 1960s (fig. 1) (Sheridan et al., 1995; Shirmohammadi et al., 1986; Sheridan and Hubbard, 1987). The 334 km^2 LRW is the primary agricultural experimental watershed in the Coastal Plain region of the southeastern U.S. Almost year round production of vegetables and row crops has led to extensive and sustained use of fertilizer and pesticides. Increased animal production has elevated the risks associated with nonpoint−source pollution (Kellogg et al., 1994). Rainfall is unevenly distributed and often occurs as short−duration, high−intensity convective thunderstorms (Bosch et al., 1999). These thunderstorms promote runoff and erosion that may carry soluble and sorbed phases of applied nutrients and pesticides to lower landscape positions or into surface waters.

The landscape is dominated by a dense dendritic network of stream channels bordered by riparian forest wetlands, with upland areas devoted to mostly agricultural uses. Riparian areas provide storage for storm runoff from adjacent upland areas and have great potential for buffering the impacts of

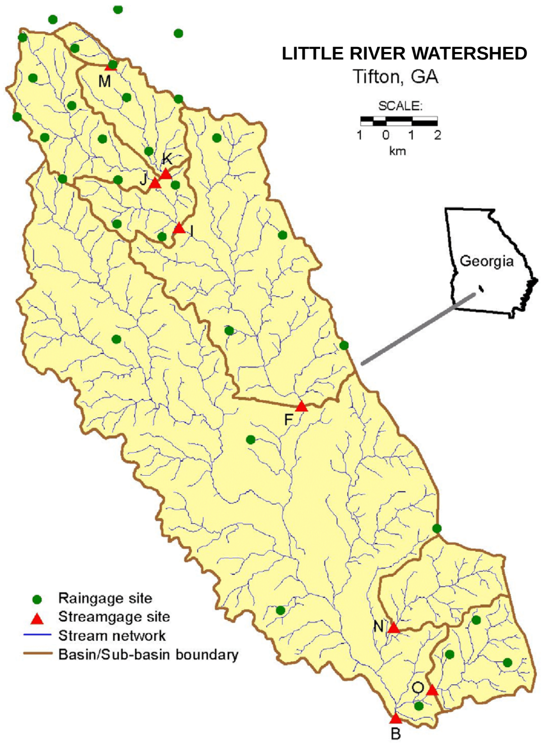

Figure 1. Little River experimental watershed.

runoff from agricultural areas (Asmussen et al., 1979; Yates and Sheridan, 1983; Gilliam, 1994).

For purposes of this analysis, we concentrated on the 22.1 km^2 subwatershed J in the headwaters of the watershed, where higher resolution input data were available. The channel length for this watershed is approximately 10 km, and the average channel slope is 0.4%. Land−use data specifying the crop types in each field of the watershed were collected each year from 1997 to 2002. This watershed is approximately 30% row crop, 2% pasture, and 67% forested. The remainder is water and pecan orchards.

Modeling Framework

SWAT 2000 within BASINS 3.0 was used for the model simulations. BASINS 3.0 uses ArcView GIS to convert geographic coverages into model input. Simulations with SWAT were conducted for a six−year period, from 1997 to 2002. These years coincided with available field−specific land−use survey data. The accuracies of the simulated streamflow and water budgets were examined for this period. A comparison was made between simulated results obtained using a default parameter set determined by BASINS and simulated results obtained using a parameter set modified to reflect initial conditions in the shallow surficial aquifer at the time the simulation began. In addition, results of a SWAT simulation obtained using higher spatial resolution input data sets assembled by the Southeast Watershed Research Laboratory (SEWRL) were compared with those obtained using the lower spatial resolution data sets readily available with BASINS. The differences in the input parameter sets were in the resolution of the land−use, soils, and topographic coverages. For both cases, the low and high resolution, observed precipitation and temperature data collected within the watershed were used. Comparison of the two scenarios provides a means of examining the degree of accuracy that can be expected through use of the readily available data sets available within the BASINS system and possible benefits of assembling higher detail data sets. An outline of the simulation scenarios conducted including the various spatial resolutions and the modifications to the initial parameter sets are presented in table 1.

GIS Data

The BASINS watershed utilities were used to define the simulation area and to prepare the input data required for the SWAT runs. The BASINS modeling system provides topographic, soils, and land−use data for each 8−digit HUC watershed within the lower 48 states of the U.S. (www.epa.gov/waterscience/ftp/basins/gis_data/huc).

The first step in creating the model input is the watershed delineation accomplished using digital elevation data. Digital elevation model (DEM) data is a requirement for the watershed delineation process of BASINS. The low−resolution simulation utilized the 90 m grid DEM data available from the EPA. The high−resolution coverage was generated using a 30 m grid DEM obtained from the Georgia GIS Clearinghouse (http://gis.state.ga.us/Clearinghouse/clearinghouse.html) (fig. 2).

For both cases, several steps were taken to obtain a better representation of the watershed hydrography. A digitized stream coverage created from a USGS 1:24000−scale topographic quadrangle map was used. In order to accurately represent the stream configuration, the network for each basin outlet needed to be extended beyond the point of the

Table 1. Simulation designations and descriptions of the modeling scenarios conducted to examine the impact of input data resolution and initial groundwater conditions.

Scenario	Description	Initial Groundwater Conditions	Digital Elevation Data	Land Cover Data Set	Soil Data Set	Hydrologic Response Units (HRUs)
LRD	Low−resolution input data, default initial conditions.	Default	EPA 90 m grid	USGS GIRAS	STATSGO	58
HRD	High−resolution input data, default initial conditions.	Default	Georgia Clearinghouse 30 m grid	Land−use Field Surveys	SSURGO	100
HRM	High−resolution input data, modified initial conditions.	Modified for high water table conditions.	Georgia Clearinghouse 30 m grid	Land−use Field Surveys	SSURGO	100
HRO	High−resolution input data, mixed initial conditions.	Modified for high water table in 1997 and 1998; default initial conditions for 1999−2002.	Georgia Clearinghouse 30 m grid	Land−use Field Surveys	SSURGO	100

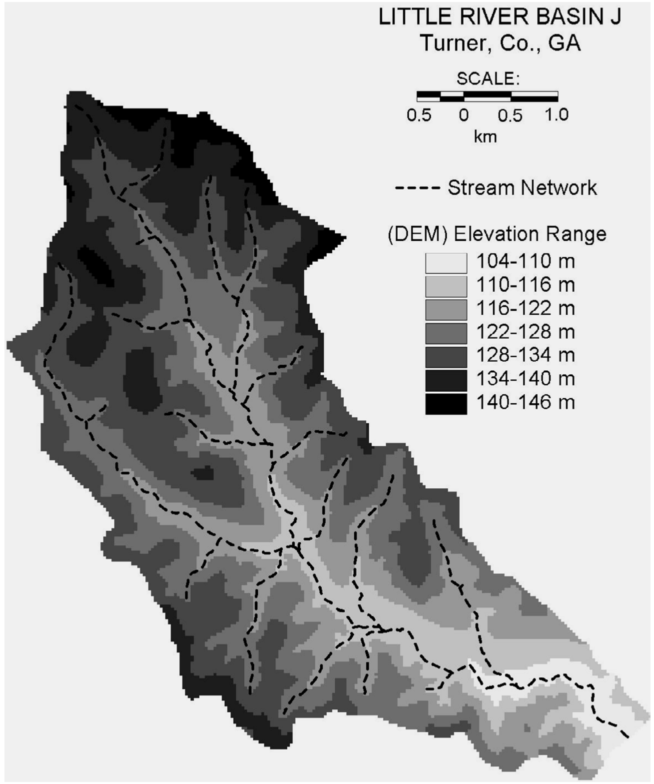

Figure 2. Little River watershed J 30 m grid digital elevation model used for the high spatial resolution simulation.

actual outlet. This extension allowed the program to more accurately compute the stream location and watershed delineation during the modeling process. Watershed boundaries generated by the model were visually compared to a digitized watershed boundary, which had been field checked and adjusted for the influence of roads and railroads. In order to get the proper stream drainage and watershed boundary for the simulation, two available options were used. First, the masking option was utilized to eliminate edge effects. Second, the burn−in option available within BASINS was used to generate the correct stream coverage. This allows the model to generate a stream coverage for streamflow routing that closely overlaps the digitized coverage. When these options were used, a stream coverage consistent with the digitized coverages was obtained. Subbasins and monitoring sites were selected by defining drainage points within the coverage. The watershed was subdivided into 29 subwatersheds for simulation purposes.

Because of the relatively flat topography, the basin boundary was buffered to properly analyze the topographic features of the edges of the basins. Basin J was buffered by a distance of 300 m. These buffered boundaries were used in the automatic watershed delineation process of BASINS, serving as a mold for creating a mask over the digital elevation data. Only those elevations within the masked area are used for model computations. This step allowed the model to more accurately compute the drainage basin boundary.

The land−use coverages used for each basin in the modeling process differed considerably between the low and the high resolution model runs. The low−resolution land−use data set was from the 1:250,000−scale USGS GIRAS data set for 1977−1980 (fig. 3). These data yielded a single land−use coverage for the entire six−year simulation period. The original data had areas without a classification code, making it unsuitable for use with BASINS. These data were revised by adding land−use codes for those areas. An ArcView function was used to clip the large−area land−use coverage to the same area as the buffered basin boundary.

The high−resolution land−use data set was obtained from actual land−use surveys conducted from 1997 to 2002 (fig. 3). The field delineations were created using digital ortho−photos. The field observations covered tilled fields, pastures, and orchards. The areas covered by water were obtained from digital line graphs (DLGs) available through the Georgia GIS Clearinghouse. The remainder of the basin area was assigned a cover class of forest−evergreen. The coverages were converted into a format consistent with SWAT land−use designations using user−provided look−up tables. The actual land−use within the watershed varied from year to year (table 2).

Two soils coverages were used for the analysis. The soils data provided within BASINS is the USDA Natural Resources Conservation Service (NRCS) STATSGO data (www.epa.gov/waterscience/ftp/basins/statsgo). The minimum area mapped in the STATSGO data set is approximately 625 ha (fig. 4). For basin J, the county−level Soil Survey Geographic (SSURGO) soils data were available from the Georgia GIS Clearinghouse (fig. 4). Field mapping methods using national standards are used to construct the soil maps in the SSURGO data base. Mapping scales generally range from 1:12,000 to 1:63,360. SSURGO is the most detailed level of soil mapping done by the NRCS. SSURGO digitizing duplicates original soil survey maps. The STATSGO coverage indicates that Tifton loamy sand extends through 78% of the watershed, while the SSURGO coverage indicates that it

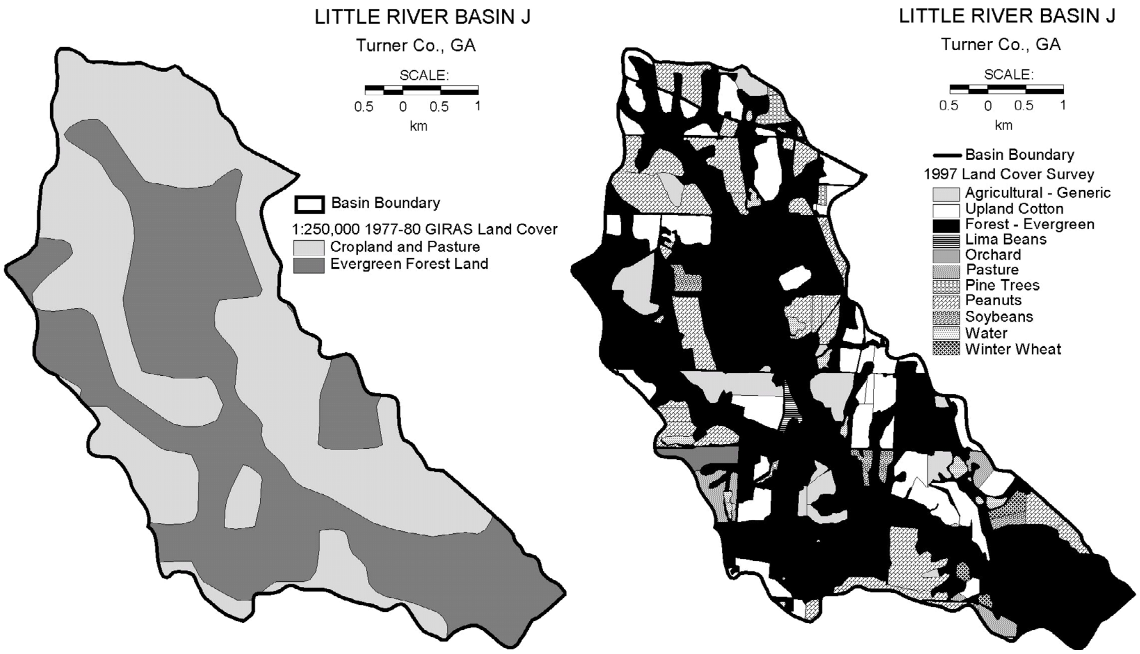

Figure 3. Watershed J low and high resolution land−use coverages.

covers 54% of the watershed. Soils in the watershed are generally poorly drained with sandy, high−conductivity surface soils and lower−conductivity subsoils.

The soils data set was clipped using ArcView to cover only the area of the buffered basin boundary. A relational attribute, S5ID, was added to the SSURGO data, allowing a relational link to the U.S. soils database. Identification codes consistent with those used within SWAT were incorporated into the GIS coverages for purposes of developing the hydrologic characteristics of the soils.

Precipitation input files for all simulations were built for watershed J using observed data from 1997 to 2002. Weighted daily averages were calculated using data from all gauges within the basin (fig. 1). Maximum and minimum air temperatures were obtained from the University of Georgia Tifton weather station (www.griffin.peachnet.edu/bae/), which is located on the lower end of the Little River watershed. In the process of defining the weather database, the U.S. database provided with BASINS was selected and served as the base for simulation of solar radiation, wind speed, and relative humidity.

Watershed Division

The SWAT model divides the watershed into hydrologic response units (HRUs). While each subwatershed may contain multiple HRUs, flow from each HRU is routed directly into the channel system of that subwatershed. These HRUs are determined by combinations of land−use and soil type. In order to avoid a large number of HRUs, minor land−use categories and soil types are ignored. The thresholds for ignoring these classifications are selected by the user. Land−uses and soils that cover a percentage of the subbasin area less than the threshold level are eliminated. In determining the hydrologic response units (HRUs) determined by SWAT, the threshold for land−use was set at 10% and that for soils was set at 18% for all simulation scenarios. These values were established based on guidance provided by the model developers (Arnold, personal communication). Runoff, erosion, and agrichemical transport are determined separately for each HRU and routed to obtain the total watershed runoff. A minimum HRU size of 40 ha was assumed. For the low−resolution (SWAT LRD) case, using the GIRAS land−use and STATSGO soils data sets, 58 HRUs were generated. For the high−resolution land−use and soils data sets (SWAT HR), approximately 100 HRUs were generated.

Table 2. Input land−use for watershed J and SWAT reclassification (in parenthesis) with thresholds set at 10% for land−use and 18% for soils.

Land−use	Low−Resolution Data Set	Land−Use Survey Data (% of land area) 1997	1998	1999	2000	2001	2002
Vegetables	0 (0)	0.32 (0)	2.98 (2.72)	1.23 (1.29)	0 (0)	3.50 (2.29)	2.65 (1.78)
Soybean	0 (0)	1.04 (0)	1.03 (0.27)	0.79 (.94)	0.34 (0)	0 (0)	0 (0)
Pasture	0 (0)	1.64 (1.35)	0.71 (0)	0.56 (0)	1.54 (1.11)	1.33 (0.86)	1.90 (1.79)
Water	0 (0)	1.09 (0)	1.09 (0)	1.09 (0)	1.09 (0)	1.09 (0)	1.09 (0)
Peanut	0 (0)	13.20 (13.72)	14.91 (14.56)	11.66 (12.04)	2.86 (1.62)	8.20 (6.09)	7.85 (5.92)
Forest	48 (48)	61.31 (67.72)	61.23 (66.75)	61.85 (65.51)	64.27 (68.55)	64.33 (69.51)	63.63 (68.54)
Upland cotton	0 (0)	14.25 (13.59)	12.88 (12.30)	19.34 (17.94)	24.69 (25.18)	20.51 (20.82)	20.18 (20.07)
Generic agric. land	52 (52)	5.68 (3.17)	4.44 (2.94)	2.04 (1.41)	4.02 (3.10)	0.31 (0)	1.97 (1.46)
Orchard	0 (0)	0.74 (0.44)	0.74 (0.47)	0.74 (.44)	0.74 (0.44)	0.74 (0.44)	0.74 (0.44)
Winter wheat	0 (0)	0.56 (0)	0 (0)	0.71 (.43)	0.45 (0)	0 (0)	0 (0)

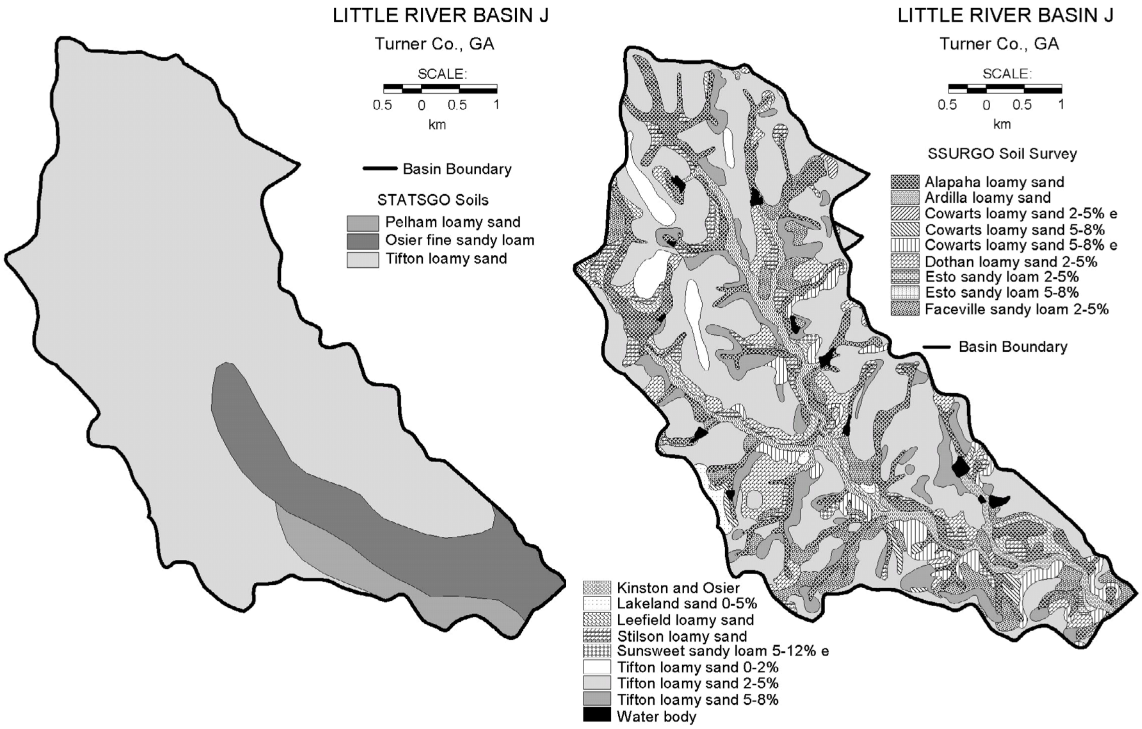

Figure 4. Watershed J low and high resolution soils coverages.

Parameter Modification for Initial Conditions

In order to incorporate specific land−use coverages for each year, the model had to be run for single years. The model simulation requires a number of days to properly initialize several of the parameters within the model to accurately represent the conditions being simulated. These parameters represent conditions at the time the simulation begins, such as groundwater depth, soil saturation, and plant growth. The accuracy at the beginning of the simulation can be improved by improving the estimates of the initial conditions. For longer simulations, this is not a significant consideration. However, for single−year simulations, some error is introduced while the model initializes. For our simulations this initialization period dramatically affected the baseflow and streamflow by impacting the aquifer water−holding capacity. Three parameters appear to be critical in this process: the initial depth of water in the shallow aquifer (SHALLST), the groundwater delay or the time required for water leaving the bottom of the root zone to reach the shallow aquifer (GW_DELAY), and the initial water storage in the vadose zone (FFCB). Each of these parameters affects to some degree the characteristics of the alluvial aquifer. The defaults in the SWAT model and the adjustments made to these values are shown in table 3. SWAT assumes that the shallow water table has a minimal (0.5 mm) amount of water in it at the beginning of the simulation. Because our simulations were run for a year at a time, the shallow water table began each year with only 0.5 mm of water. In addition, because of the fairly large default GW_DELAY parameter (31 days), the flow of the percolated water through the shallow water table and into the streamflow was delayed. SWAT calculates the default initial soil water content (FFCB) as a function of the annual precipitation. For the six−year simulation, the default FFCB averaged 50%. All of these factors lead to a delay between percolation and shallow groundwater flow into the stream.

In January during wet years, the shallow aquifer and the vadose zone in most Coastal Plain watersheds are near saturation. To account for this, SHALLST was increased from 0.5 mm to the maximum value (1000 mm) for all of the HRUs, and the fraction of the pores in the vadose zone holding water at the beginning of each annual simulation was increased by changing FFCB from 50% to 95%. These modifications only affect the beginning portion of the simulation, until the model recalculates the percent saturation and the water table depth. In addition, in many parts of the watershed, the water table is directly below the rooting zone. Flow into this aquifer from the root zone is rapid. To account for this, GW_DELAY was decreased from 31 days to 1 day. It was also noted that the total number of heating units needed to bring the pine tree land−use to maturity was set at 0 in the .mgt file. The model defaults these values to a minimum heating unit value during simulation. However, in order to account for initial plant growth, these values were changed to 3500.

Table 3. SWAT default parameters and modifications of the initial conditions used for watershed J.

Parameter	Default Initial Groundwater Conditions	Initial Conditions Modified for High Water Table
SHALLST; initial depth of water in the shallow aquifer (mm)	0.5	1000
GW_DELAY; groundwater delay (days)	31	1
FFCB; initial water storage in the vadose zone (%)	50	95

Model Performance

The accuracy of the model simulations were evaluated using several standard techniques. The difference between the observed and simulated daily streamflow volumes and the least squares error (LSE) were calculated and evaluated over the simulation period to examine trends. The LSE is calculated as:

$$\mathrm{LSE} = \sum_{i}^{n} (O_i - S_i)^2 \tag{1}$$

where O_i and S_i are the observed and simulated daily flows for the ith day, respectively, and n is the total number of days. For the different simulation scenarios, the mean absolute error (MAE; Weglarczyk, 1998) was calculated as:

$$\mathrm{MAE} = \frac{\sum_{i}^{n} ABS(O_i - S_i)}{n} \tag{2}$$

Both LSE and MAE are expected to approach zero as the accuracy of the simulation improves. The model efficiency (E; Nash and Sutcliffe, 1970) was calculated as:

$$E = 1 - \frac{\sum_{i}^{n} (O_i - S_i)^2}{\sum_{i}^{n} (O_i - O')^2} \tag{3}$$

where O' is the mean of the observed daily flow over the simulation period. The efficiency can be thought of as the sum of the deviations of observations from a linear regression line with a slope of 1. Efficiencies equal to 1 indicate a perfect fit between the observed and predicted data, while values equal to 0 indicate that the model is predicting no better than using the average of the observed data. Negative efficiencies generally indicate that the average value of the output is a better estimate than the model prediction.

Results

Default Parameter Conditions

Simulations were conducted for the period from 1997 to 2002 using the default parameters established by BASINS with the high spatial resolution SEWRL land−use, soils, and topography data (table 4). For the observed data, total water yield (TWY) was obtained from streamflow measurements. Values for the observed stormflow and baseflow were determined from measured TWY using water budgets established through prior research on the watersheds (Shirmohammadi et al., 1984). Stormflow was assumed to be 35% of the TWY for watershed J. The remainder of the TWY was assumed to come from baseflow (65%). Observed evapotranspiration was calculated from the difference between precipitation and TWY, assuming the storage within the vadose zone and the groundwater did not vary from year to year, and recharge into the deep aquifer was 1% of annual precipitation (Sheridan, 1997). On an annual basis, there may be some inaccuracy in these assumptions. However, the assumptions should be reasonable for long−term averages.

Using the high−resolution land−use, soils, and topography data and the default initial parameters sets (HRD), the simulated TWYs for watershed J were within 20% of the annual water balance each year for the six years from 1997 to 2002 (table 4, fig. 5). The greatest difference was observed in 1997, when the observed TWY was 52% of the water balance and the simulated TWY was 32% of the water balance (table 4). The greatest deviation was observed in the baseflow or groundwater component (table 4). Stormflow estimates were fairly accurate (within 8% of the annual water balance). Observed differences in 1997 and 1998 were primarily due to underestimation of the baseflow component, while differences observed in 1999 through 2002 were due to combined overestimations in the stormflow and baseflow components.

Modified Initial Conditions

The SWAT parameters SHALLST, GW_DELAY, and FFCB were modified for all six years of the simulation to reflect the wet conditions normally observed at the beginning of the calendar year (table 3). The results obtained using the high spatial resolution coverages with the modified parameters for initial conditions (HRM) are illustrated in table 5. As expected, by increasing the depth of water in the shallow aquifer at the beginning of the simulation and decreasing the available storage in the vadose zone, baseflow and TWY were increased. The increase was observed in the first months of the simulation, when the impact of the initial parameter

Table 4. Comparison between the observed and simulated streamflow components for watershed J from 1997 to 2002 resulting from the SWAT simulations with high spatial resolution input data and the default initial conditions (HRD). Values in parentheses indicate the percentage of total annual rainfall made up by that characteristic.

	1997		1998		1999		2000		2001		2002	
	Obs.	SWAT	Obs.	SWAT	Obs.	SWAT	Obs.	SWAT	Obs.	SWAT	Obs.	SWAT
Rainfall (mm)	1518	1515	1372	1372	913	920	1041	1039	952	954	1047	1047
Stormflow (mm)[a]	275 (18%)	232 (15%)	251 (18%)	234 (17%)	35 (4%)	66 (7%)	54 (5%)	131 (13%)	72 (8%)	93 (10%)	42 (4%)	87 (8%)
Baseflow (mm)[b]	511 (34%)	246 (16%)	466 (34%)	277 (20%)	65 (7%)	86 (9%)	100 (10%)	140 (13%)	133 (14%)	130 (14%)	78 (7%)	102 (10%)
Total water yield (mm)	786 (52%)	478 (32%)	716 (52%)	510 (37%)	101 (11%)	152 (17%)	153 (15%)	271 (26%)	205 (22%)	222 (23%)	120 (12%)	189 (18%)
ET (mm)[c]	716 (47%)	758 (50%)	642 (47%)	745 (54%)	803 (88%)	676 (73%)	877 (84%)	623 (60%)	737 (77%)	671 (70%)	916 (87%)	684 (65%)

[a] Observed stormflow calculated as 35% of observed total water yield based on data of Shirmohammadi et al. (1984).
[b] Observed baseflow calculated as 65% of observed total water yield based on data of Shirmohammadi et al. (1984).
[c] Observed evapotranspiration calculated by difference between precipitation and total water yield with 1% deep aquifer recharge.

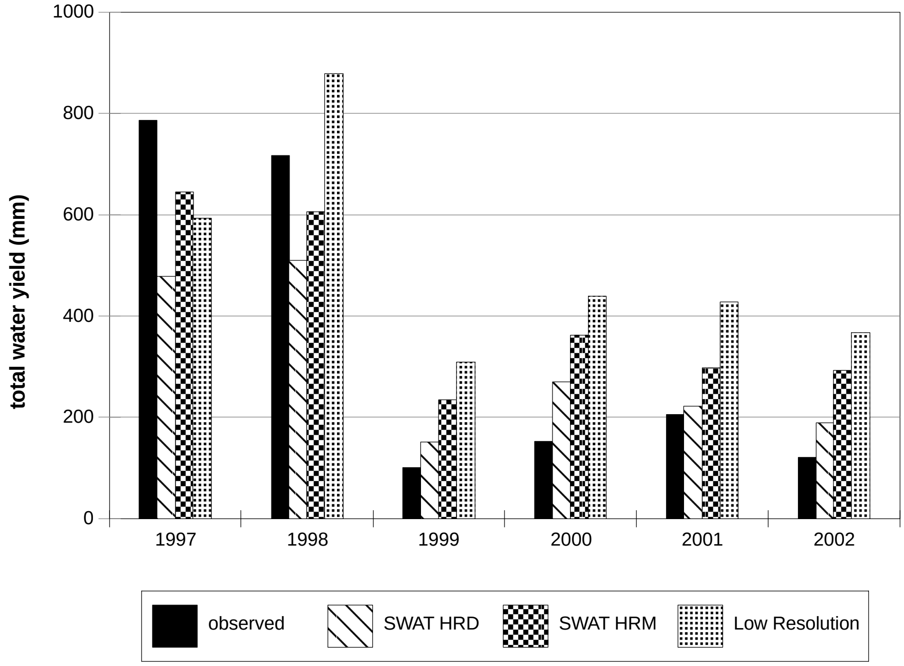

Figure 5. Comparison between the observed and SWAT−simulated total water yield for watershed J, simulated using the high spatial resolution input with the default initial parameters (HRD), the high spatial resolution input with the modified initial parameters (HRM), and the low spatial resolution input with default initial parameters (LRD).

estimates effects the results. During 1997 and 1998, which were higher precipitation years, this increased the accuracy of the simulations. However, during the four drier years from 1999 to 2002, this decreased the simulation accuracy. Changing the initial groundwater parameters increased the simulated baseflow by 66% in 1997 and by 31% in 1998. Similar increases were observed in simulated TWYs. While improvements were obtained for the wet years, greater deviations in TWY were observed for 1999 through 2002 when the initial groundwater conditions were modified for these years (fig. 5).

For the entire six−year simulation period, simulated stormflow obtained using the modified initial conditions was 13% of the precipitation total, while the observed stormflow was 11% (fig. 6). Simulated TWY exceeded observed TWY by 6%, 36% for the simulated results obtained using the HRM simulation versus 30% observed. This was largely due to an overestimation during the drier years (fig. 5). A comparison between ET determined through difference and simulated ET indicates a slight underestimation in the ET for the watershed. A decrease in simulated TWY would be expected if simulated ET were increased, which would improve the simulation results for the six−year period. However, some of the year−to−year differences in ET may have been due to actual changes in water storage over the simulation period. The observed data assume that the water storage remains the same. From year to year, this would not be correct. Stored water would decrease during dry years and increase during wet years. Over the long term, this would be expected to balance out.

An improved fit was obtained using the modified initial parameter set for 1997 and 1998 and the default parameter set for 1999 through 2002 (HRO). This assumption decreased available vadose zone storage in 1997 and 1998, but retained

Table 5. Comparison between the observed and simulated streamflow components for watershed J from 1997 to 2002 resulting from the SWAT simulations with high spatial resolution input data and the modified initial conditions (HRM). Values in parentheses indicate the percentage of total annual rainfall made up by that characteristic.

	1997		1998		1999		2000		2001		2002	
	Obs.	SWAT	Obs.	SWAT	Obs.	SWAT	Obs.	SWAT	Obs.	SWAT	Obs.	SWAT
Rainfall (mm)	1518	1515	1372	1372	913	920	1041	1039	952	954	1047	1047
Stormflow (mm)[a]	275 (18%)	238 (16%)	251 (18%)	242 (18%)	35 (4%)	72 (8%)	54 (5%)	138 (13%)	72 (8%)	106 (11%)	42 (4%)	94 (9%)
Baseflow (mm)[b]	511 (34%)	408 (27%)	466 (34%)	364 (27%)	65 (7%)	163 (18%)	100 (10%)	224 (22%)	133 (14%)	193 (20%)	78 (7%)	199 (19%)
Total water yield (mm)	786 (52%)	645 (43%)	716 (52%)	605 (44%)	101 (11%)	234 (25%)	153 (15%)	362 (35%)	205 (22%)	298 (31%)	120 (12%)	293 (28%)
ET (mm)[c]	716 (47%)	760 (50%)	642 (47%)	748 (55%)	804 (88%)	678 (74%)	877 (84%)	630 (61%)	737 (77%)	679 (71%)	916 (87%)	684 (65%)

[a] Observed stormflow calculated as 35% of observed total water yield based on data of Shirmohammadi et al. (1984).
[b] Observed baseflow calculated as 65% of observed total water yield based on data of Shirmohammadi et al. (1984).
[c] Observed evapotranspiration calculated by difference between precipitation and total water yield.

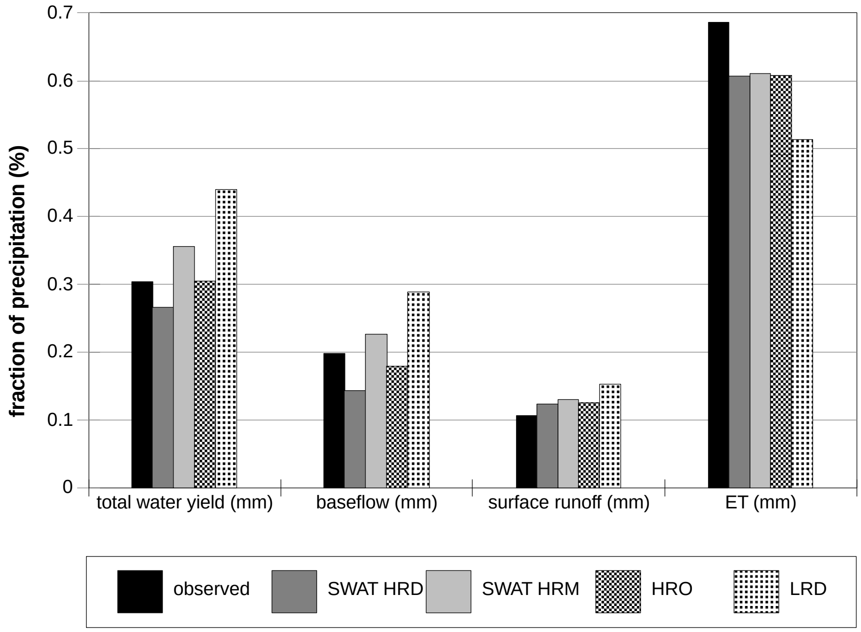

Figure 6. Six−year average hydrologic budgets for the simulated and observed data.

the default conditions for 1999 through 2002. There is considerable justification for this selection. Precipitation totals in 1997 and 1998 were slightly above the long−term average of 1228 mm, while the remaining four years were well below average. Dry winters were observed during each of the drought years (Bosch et al., 2003). In addition, measured water table conditions during each of these four years were well below saturation in all years but 2001 (Bosch et al., 2003).

The HRO simulation yielded the same results as the HRM simulation for 1997 and 1998 and the same results as the HRD simulation for 1999 to 2002. Six−year TWYs were improved over the other simulation scenarios (fig. 6). A comparison between the observed and simulated total daily flows obtained using the HRO scenario for 1997 and 2001 is illustrated in figure 7. While the model predicted the trends in the observed data, there were inconsistencies between the magnitude and the duration of the observed and simulated daily flows. The model generally overpredicted discharge on the watershed in the summer period, particularly zero−flow conditions. Examination of daily flows indicated that during drier years, observed baseflow conditions in the watershed were not as persistent as those simulated by the model (fig. 7). During these dry periods, the model simulated fairly large flow events in response to rainfall when none was observed. The model underpredicted some of the larger peak flows observed during the winter months in 1997 but overestimated storms in early 2001. Observed streamflow rose and fell rapidly in the watershed and did not persist as long as was simulated. The simulated stormflow component of the hydrograph rose and fell too rapidly, while the baseflow component did not recede rapidly enough (fig. 7).

The goodness of fit parameters calculated using the daily flow volumes for all simulation scenarios are shown in table 6. The best fit based on the LSE was obtained using the HRO parameter set (LSE = 19,377). This was a slight improvement over the results obtained using the modified initial conditions (LSE = 19,690) or the default initial conditions (LSE = 21,517). While the calculated model efficiencies for the daily flow volumes were poor (table 6), this appears to be largely due to missing the timing of the hydrograph peaks and inaccuracies in the estimation of baseflow conditions throughout the summer (fig. 7).

To better evaluate how well simulated values represented observed conditions, comparisons were also made between monthly observed and simulated flow volumes. Monthly simulated totals for the entire period indicated that the SWAT model with the high−resolution input characterizations generally simulated the trends observed in the water yield quite well (fig. 8). Model efficiencies (*E*) for the monthly data were 0.80 for the HRO simulation, indicating good agreement with the observed monthly flows (table 7). However, during the higher precipitation years (1997 and 1998), the model underpredicted the spring runoff peaks, while during the lower precipitation years, the model generally overpredicted the peaks (fig. 8). In addition, actual baseflow conditions during the drier years persisted for shorter periods than were simulated (fig. 8). As indicated by the mass balance data (fig. 5), wetter years were underpredicted, while drier years were overpredicted.

Large errors between the simulated and the observed flow volumes were also observed in 1997 and 1998 in the first month of the simulation as the model re−initialized. This discrepancy led to fairly high errors in the monthly estimate, particularly for the HRD simulation. These errors were less for the scenarios where the modified initial conditions were incorporated to account for high water table conditions and for dry years where baseflow was not as pronounced at the beginning of the year (fig. 8). However, even with the initial conditions modified for the high water table conditions, the simulated flow volumes still took up to two months to approach the observed values while the simulated water table conditions stabilized.

Impact of Input Detail

The impact of improving the accuracy of the watershed land−use, soils, and topographic representations was examined by comparing results with and without these characterizations for watershed J. A comparison was made

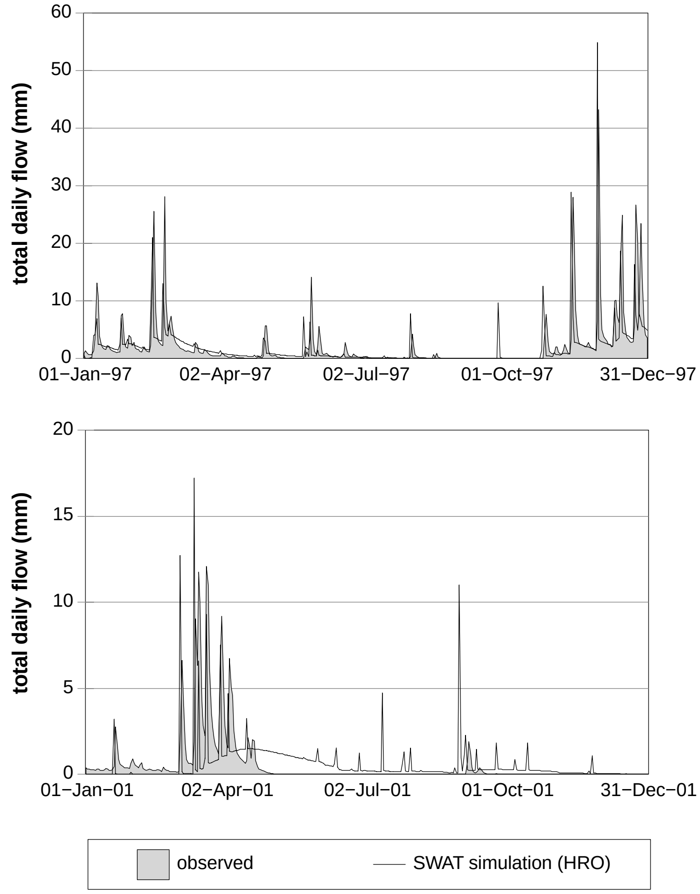

Figure 7. Comparison between observed and simulated total daily flow for watershed J during a wet (1997) and a dry (2001) year resulting from the SWAT simulation obtained using the high spatial resolution data set and the mixed initial conditions (HRO).

between the results obtained using the high−resolution data for watershed J versus the results obtained using the baseline data provided with BASINS (LRD). During the wet years (1997 and 1998), the annual simulated TWY using the low spatial resolution data (LRD) was similar in accuracy to the results obtained using the higher spatial resolution data with the default initial conditions (HRD) (fig. 5). However, in the dry years, the simulated TWY obtained using the lower spatial resolution data overestimated the observed TWY by approximately 100% (fig. 5). Using the high spatial resolution data with the default initial conditions (HRD) improved the annual results for all years except 1997 (fig. 5). An improvement was observed for the wet years when the modified initial conditions (HRM) were incorporated into the simulation (fig. 5).

Based on comparisons of the daily data, the simulated TWYs generated using the lower resolution land−use, soils, and topography (LRD) were less accurate than the high−resolution results (table 6). Using the monthly data, the LSE for the low−resolution simulation (LRD) was less than that for the high−resolution simulation with the default initial conditions (HRD) (table 7). This is partially due to the error in the HRD simulation during the early period of 1998 when the model re−initialized (fig. 8). While simulated monthly trends obtained with the low−resolution input data set (LRD) followed observed trends (fig. 8), deviations from observed annual TWYs were approximately twice that observed for the HRD simulation (fig. 5) for the years 1999 to 2002. The greatest error was observed in the LRD−simulated TWY, where annual deviations as high as 27% of the water balance were observed (fig. 5). Improvements were observed by

Table 6. Goodness of fit parameters for the daily simulated total flow volumes and the different simulation scenarios.

Scenario	Description	LSE (mm^2)	MAE (mm)	*E*
LRD	Low−resolution input data, default initial conditions.	23405	1.23	−0.24
HRD	High−resolution input data, default initial conditions.	21517	1.06	−0.14
HRM	High−resolution input data, modified initial conditions.	19690	0.94	−0.04
HRO	High−resolution input data, mixed initial conditions.	19377	0.94	−0.03

Table 7. Goodness of fit parameters for the monthly simulated total flow volumes for the different simulation scenarios.

Scenario	Description	LSE (mm^2)	MAE (mm)	*E*
LRD	Low−resolution input data, default initial conditions.	64802	23.81	0.64
HRD	High−resolution input data, default initial conditions.	82477	19.47	0.55
HRM	High−resolution input data, modified initial conditions.	37101	15.50	0.80
HRO	High−resolution input data, mixed initial conditions.	36014	14.48	0.80

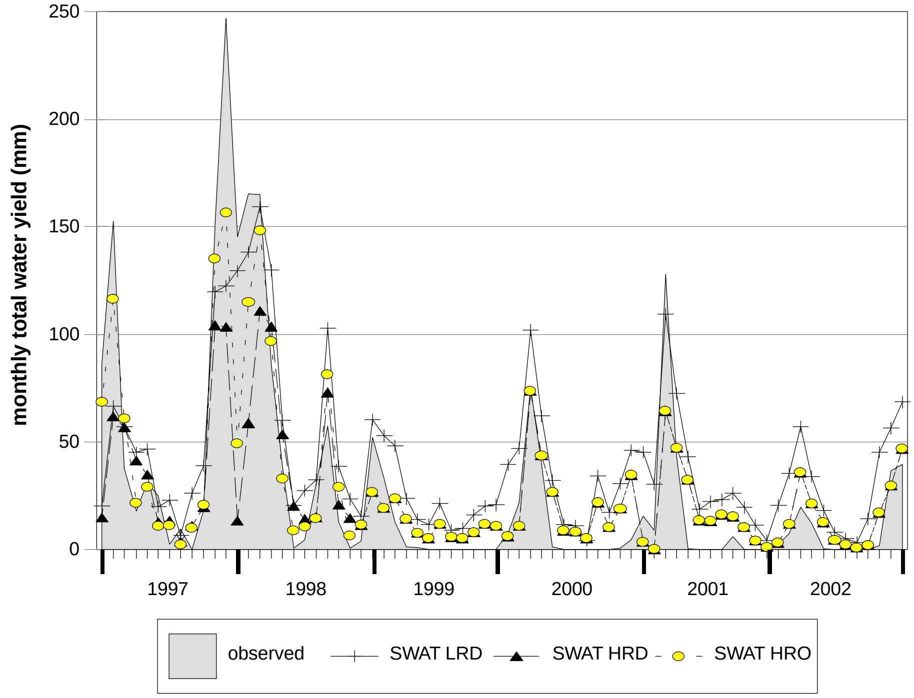

Figure 8. Observed and simulated monthly flow volumes for watershed J resulting from SWAT simulations with the low−resolution default parameter set (LRD) and from the high spatial resolution data set and the mixed initial conditions (HRO).

using the modified initial conditions. The Nash−Sutcliffe efficiency for the monthly TWYs was 0.64 for the LRD scenario versus 0.80 for the HRO scenario (table 7). Similar improvements were observed for MAE.

While results obtained using the less detailed coverages could have been improved through adjustments of the initial conditions, the corrections would have to be different from those used for the high−resolution simulations. Because the LRD simulation underestimated the TWY in 1997 and overestimated it in 1998, each of these years would have to be treated differently. However, as previously discussed, these were both relatively wet years and there is little justification for this treatment.

Discussion

On a monthly basis, the results of the HRO SWAT simulation of the hydrology of Little River watershed J resulted in an MAE of 14.5 mm. This was 40% less than the MAE obtained using the LRD data set and 26% less than that obtained using the HRD set (table 7). The large improvements obtained using the higher resolution input data indicate that a significant improvement can be obtained by using the higher resolution input data versus the basic information readily available with the BASINS system. Annual (fig. 5) and six−year totals (fig. 6) of TWY were more accurate with the higher resolution data sets. By developing year−to−year coverages, the calibration process can directly address changes in land−use. This should prove to be important for developing TMDLs across the U.S., which uses land−use and management changes as a tool to improve water quality. Accurate representations of land−use improved the accuracy of the hydrologic simulations, particularly when combined with adjustments for existing groundwater conditions. Similar results were found by Suttles et al. (2003). Their study, which applied the annualized Agricultural Nonpoint Source Pollution (AnnAGNPS) model, also found that accurate representations of land−use were necessary to obtain accurate hydrologic simulations within this region.

While the model predicted the trends in the data very well, there were some inconsistencies between the observed and simulated daily flow volumes (fig. 7). For all scenarios examined, the model tended to overpredict the discharge conditions typically observed on the watershed in the summer period, particularly the periods when no flow was observed (fig. 8). The model also tended to underpredict the largest flow volumes. It was clear from examination of the daily data that during drier years the baseflow conditions in the watershed were not as persistent as those simulated by the model (fig. 7). During these dry periods, the model simulated fairly large flow events when none was observed. Streamflow rises and falls rapidly in the watershed and does not persist as long as was simulated. This may have fairly serious implications with regard to TMDLs, where accurate assessments of daily loads are necessary.

During dry periods when the stream was not flowing and significant precipitation occurred, runoff was typically simulated while none was measured. These inaccuracies are illustrated by the cumulative probability density data for the observed and simulated (LRD and HRO) daily flow rates for the six−year period (fig. 9). The greatest deviation in the curves occurs in the smaller events, less than 2 mm. This largely reflects the inaccuracy observed for the summer simulations when several small flow events were simulated which did not occur. The discrepancy between the LRD and the HRO simulations is also illustrated by this graph.

A contributing factor to the inaccuracy appears to be the direct routing of surface runoff from the HRUs into the stream by SWAT. In this and many other Coastal Plain watersheds, most upland surface runoff and subsurface flow

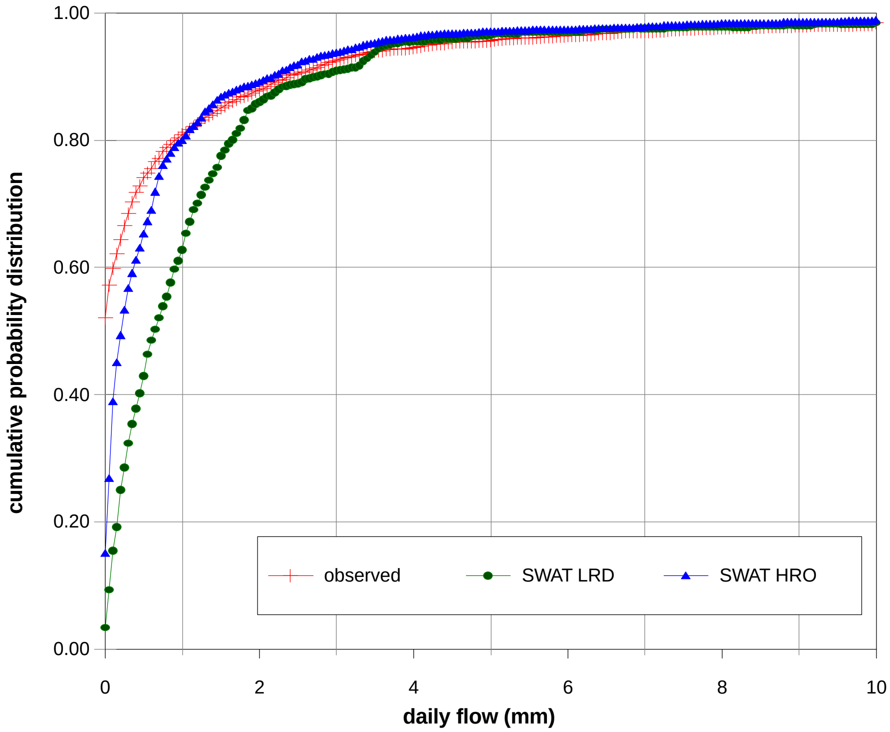

Figure 9. Cumulative probability distribution function for the observed and simulated daily flow depths.

has to travel through dense riparian buffers prior to entering the stream. When the shallow aquifer water table is high, which is a normal condition from December to April, surface runoff can flow directly to the stream after flowing through the buffer. Saturated conditions within the riparian buffer can lead to rapid stormflow runoff. The results of Shirmohammadi et al. (1986) stressed the importance of the conditions of the alluvial aquifer, indicating that the amount of streamflow is heavily dependent on the degree of saturation within this aquifer. If the aquifer parameters are properly set, this phenomenon appears to be well represented by the model. When storage is available within the shallow aquifer, the runoff normally infiltrates into the soil as it flows through the buffer. This infiltrated water may simply be stored in the aquifer or return as baseflow. Currently there is no component within the model to simulate infiltration of surface runoff between the upland and the stream. This would lead to the overprediction of storm and streamflow that was observed for the summer period. Because the simulations underpredicted the observed data during portions of the year and overpredicted the observed data during other portions of the year, further calibration of the model would likely yield mixed results. An increase or a decrease in the curve number function would yield a consistent increase or decrease for the entire year. However, modifications in the ET component may achieve the desired results.

A second, and related, factor may be the method used to determine HRUs. Using the dominant land−use, soils, and topography to determine the HRUs, smaller strips of land get lumped into the dominant classification. For watersheds such as those in the Coastal Plain, the riparian buffers would fall into this condition. These buffers, with characteristic soils and vegetation, would not be considered. This would be expected to impact basic hydrology, evapotranspiration, and water quality.

One of the primary factors contributing to the errors observed between the observed and the simulated flows was the hydrograph timing (fig. 10). The simulated hydrograph peaks were approximately one day prior to the observed peaks. Because of this, considerable deviation was introduced into the error calculations. While in many cases the volume was fairly close, the simulated timing was off by one day. By shifting the predicted daily flows one day forward, the LSE values for the daily data were reduced by half for the HRO simulation, and the Nash−Sutcliffe efficiency was increased from −0.03 to 0.53. The inaccuracy appears to be due to the time lag between the simulated hydrograph and the observed hydrograph. While the observed daily flows were calculated for each calendar day, the simulations occur on a 24 h basis, which is initiated by the rainfall event and does not necessarily coincide with the calendar day. Observed data indicate that the time to peak for this watershed is approximately 11 h (Sheridan, 1994). Any rainfall event occurring past mid−morning would be expected to have greater flow volume on the second day following a precipitation event than on the day of the event itself. In contrast, since the SWAT model simulates on a daily time step, the volume determined by the model for the 24 h period would include portions of the hydrograph on the rising and the falling sides of the peak, assuming it correctly simulates the time to peak. This would then lead to the discrepancies in flow volume that we have observed. In this region of the U.S., many of the thunderstorms (particularly those in the summer period) occur in the later part of the day. This would contribute to the errors that we have observed. Similar results have been observed when comparing daily and monthly flow volumes for SWAT simulations on other watersheds (Van Liew and Garbrecht, 2002).

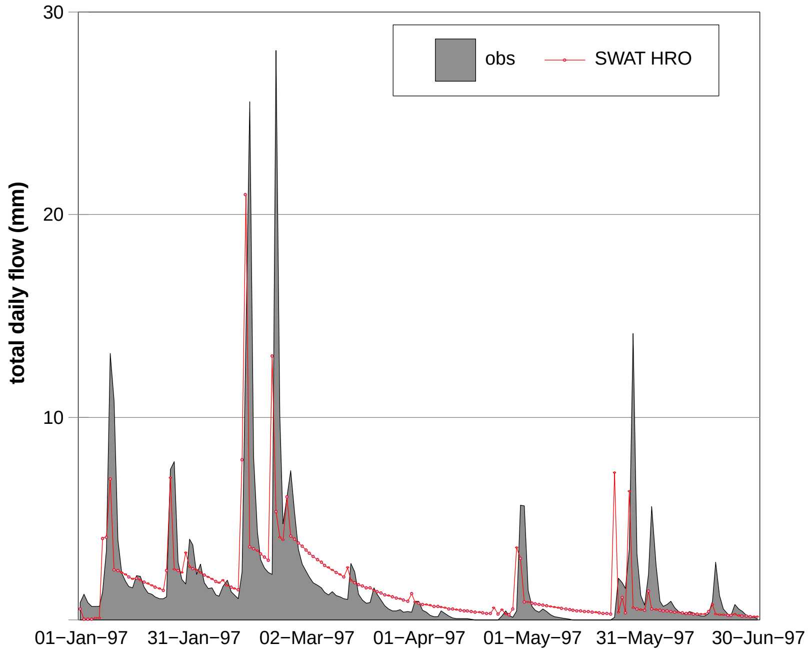

Figure 10. Observed and simulated total daily flows (HRO) from January 1 to June 30, 1997, for watershed J.

CONCLUSIONS

Results indicate that SWAT can be used to simulate streamflow within Coastal Plain watersheds and can be expected to yield reasonable estimates of monthly and annual streamflow. Accurate simulation results were obtained through a minimal amount of modification of the SWAT input parameter set describing initial characterization of groundwater conditions. The exercise focused on decreasing the amount of storage available within the surficial aquifer and decreasing the delay between percolation and subsurface flow to the stream. Water balances within 20% of the observed TWYs were obtained for the six−year simulation period using the modified inputs. Monthly model efficiencies were calculated as 0.80, indicating good agreement between the monthly totals. Daily model efficiencies were poor (*E* was approximately 0), largely due to a one−day time lag between the simulated and the observed times to peak.

A comparison was made between the simulation results that can be expected using lower resolution, readily available geographic and land−use data and those that can be expected using higher spatial resolution data. Using default initial conditions, the LSE for the daily flow simulations obtained with the LRD data set was 23,405 mm^2 versus 21,517 mm^2 for the HRD set. However, using the monthly flow data, the quality of the simulation results decreased for the same set of initial conditions (table 7). This difference was attributed to inaccurate estimates of flow in early 1998 while the model re−initialized. A significant improvement was obtained when adjustments were made to the initial conditions based on the groundwater characterizations. By using the modified initial conditions for the high precipitation years and the default initial conditions for the low precipitation years, the LSE for the daily data was decreased to 19,377 mm^2.

The combination of the more detailed spatial information along with the modified initial conditions for the high−precipitation years also yielded improved estimates of daily stormflow and subsequently TWY. Because the land−use does not change from year to year in the low−resolution data set, parameters associated with a given land−use would also not change from year to year. Thus, watershed responses that are sensitive to land−use would not be well represented through simulations such as these. While an acceptable output can be obtained, it may not accurately represent the actual land and soil characteristics of the watershed. In addition, in order to examine changes in land management as a component of the TMDL process, specific land−use characterizations must be incorporated into the simulation.

The model consistently overestimated streamflow during the summer periods, which may be an indication that baseflow conditions are not well represented by the current model structure (fig. 8). In addition, the model simulated several small flow events, which are not typically observed on the watershed (fig. 9). On this and several Coastal Plain watersheds, considerable groundwater storage typically exists during the summer period. Based on these simulation results, it appears that additional model refinement may be necessary to better represent stormflow generated within upland fields that infiltrates prior to reaching the stream and the physical processes occurring within surficial aquifers within the alluvial storage along streams within the Coastal Plain.

These results indicate that the streamflow simulations can be improved with knowledge of the groundwater conditions and observed streamflow data. In order to properly match hydrograph timing, specifically time to peak, detailed observations of streamflow are necessary. Since TMDLs are heavily influenced by streamflow conditions, these data are necessary to adequately calibrate watershed−scale models for different hydrologic and geophysical conditions of the U.S. if accurate TMDLs are to be developed for these watersheds.

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